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Calibration of a capacitive void fraction sensor for small diameter tubes based on capacitive signal features

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HIGHLIGHTS

- Alternative calibration of a capacitive void fraction sensor for small diameter tubes.
- Capacitance also dependent on spatial distribution of phases.
- Existing method requires knowledge of vapour quality *x* and mass flux for each measurement.
- Proposed method allows calibration solely based on capacitance signal.
- Good agreement with Rouhani–Axelsson drift flux void fraction model and existing method.

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ABSTRACT

In this paper, calibration of a capacitive void fraction sensor for small diameter tubes based on capacitive signal features is proposed. Existing calibration methods require the mass flux and vapour quality to be known, which poses serious issues for practical applications. In this work an alternative calibration technique is proposed, based on the statistical parameters of the measurement signal.

The proposed method was applied to 270 measurement points. The inner tube diameter for all these points is 8 mm, the mass flux ranges from 200 to 500 kg/m^{2}s and the vapour quality ranges between 2.5% and 97.5%. Refrigerants R134a and R410A were used. A good agreement was found, the results were compared to the Steiner version of the Rouhani–Axelsson drift flux void fraction model. The maximum average difference between the model and the predicted value was 1.3% with a standard deviation of 4%.

1. Introduction

The void fraction is an important parameter in many two-phase flow pressure drop and heat transfer correlations [1]. Furthermore it is closely related to the two-phase flow behaviour, which in turn has a strong effect on the total heat transfer rate and pressure drop [2]. A large variety of void fraction measurement techniques exist. However, most of these techniques have some typical advantages and disadvantages and research for new or improved void fraction measurement techniques is still ongoing. For example, quite a few studies have been performed on void fraction measurement techniques like: wire mesh tomography as e.g. in Ref. [3], hot wire anemometry as e.g. in Ref. [4] and optical techniques as e.g. in Ref. [5].

Capacitive void fraction methods, as used by Strazza et al. [6], are low cost and easy to implement and would therefore be a good option for industrial and simple lab scale applications. A drawback of this method is that the relation between the void fraction and the measured capacitance has to be determined for each design and application.

Canière et al. [7] designed a capacitive sensor for round horizontal tubes. A flow regime based calibration was proposed for this sensor by De Kerpel et al. [8], enabling void fraction measurements with this sensor. In this method a separate calibration curve is proposed for each flow regime. To be able to apply this technique, the vapour quality *x* and mass flux *G* need to be determined for each measurement point. It is not always practical or even possible to measure *x* and/or *G* especially for industrial applications In other words, although the calibration strategy proposed by De Kerpel et al. [8] works quite well, it cannot be applied to all cases where the capacitive sensor itself can be implemented due to practical constraints. To make the measurement technique more widely applicable, the calibration has to be independent of variables other than those measured with the sensor itself.

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Nomenclature

A	electrode area [m^2]
C	capacitance [F]
C_{liquid}	capacitance for full liquid flow [F]
C_{norm}	normalized capacitance [−]
C_{vapour}	capacitance for full vapour flow [F]
D	inner tube diameter [m]
d	distance between capacitor plates [m]
$F95$	frequency for which 95% of the frequency spectrum is lower [Hz]
G	mass flux [kg/m^{2}s]
x	vapour fraction [−]
x_{IA}	vapour fraction at intermittent–annular boundary [−]
x_{IS}	vapour fraction at intermittent–slug boundary [−]

Greek symbols

ε	void fraction [−]
$\varepsilon_{annular}$	void fraction for annular flow [−]
$\varepsilon_{intermittent}$	void fraction for intermittent flow [−]
ε_{slug}	void fraction for slug flow [−]
γ	dielectric constant (relative permittivity) [−]
μ	average [−]
σ	standard deviation [−]

Abbreviations

AVG	average of the difference between the model and calculated value
FEM	finite element method
STD	standard deviation of the difference between the model and calculated value

In this work an altered version of the calibration strategy as proposed by De Kerpel et al. [8] is presented, where the flow regime and the void fraction can be obtained based on the capacitance signal alone.

2. Flow regime based calibration strategy

The method proposed in the current work is based on De Kerpel et al. [8]. For clarity, the basic principles of this earlier work are discussed. The capacitance measured with the sensor by Canière et al. [7] depends on the spatial distribution of the phases. Because two phase flows are typically categorized into flow regimes based on the spatio-temporal distribution of the phases [9], the relation between the measured capacitance and the void fraction depends on the flow regime. Hence, a C–ε relation was determined for each flow regime using 3D Finite Element Method (FEM) simulations. This C–ε relation can then be used as a calibration curve to determine the void fraction based on the measured capacitance.

For slug flow and annular flow the assumed vapour liquid distributions are shown schematically in Fig. 1. To determine the C–ε relation for these structures, the radius of the vapour bubble/core was varied. For each combination of bubble/core and tube radius the cross sectional void fraction can be determined and the corresponding capacitance is determined using FEM simulations.

Due to the complexity of the interface, no interface structure could be proposed for intermittent flow. Because intermittent flow can be interpreted as a transitional regime between slug flow and annular flow, De Kerpel et al. [8] proposed a weighted average between a void fraction of an annular flow and a void fraction of a slug flow (Eq. (1)).

$$\varepsilon_{intermittent}(x) = \frac{(x - x_{IS})}{(x_{IA} - x_{IS})}\varepsilon_{annular} + \frac{(x_{IA} - x)}{(x_{IA} - x_{IS})}\varepsilon_{slug} \quad (1)$$

In Eq. (1) x_{IS} is the vapour quality at which the slug–intermittent flow transition occurs and x_{IA} is the vapour quality at which the intermittent–annular transition occurs. The void fraction $\varepsilon_{annular}$ is the void fraction determined using the C–ε relation for annular flow. ε_{slug} is the void fraction determined using the C–ε relation for slug flow. x_{IS} and x_{IA} are determined using a flow regime map. Although this weighting method gave good results, the vapour quality x and the mass flux G are required to be able to determine the flow regime, x_{IS} and x_{IA}. This limits the applicability of the method.

3. Sensor technology

3.1. Sensor design

The sensor used in this work was designed by Canière et al. [7] and measures the capacitance of the flow. This sensor consists of two concave electrodes between which the capacitance is

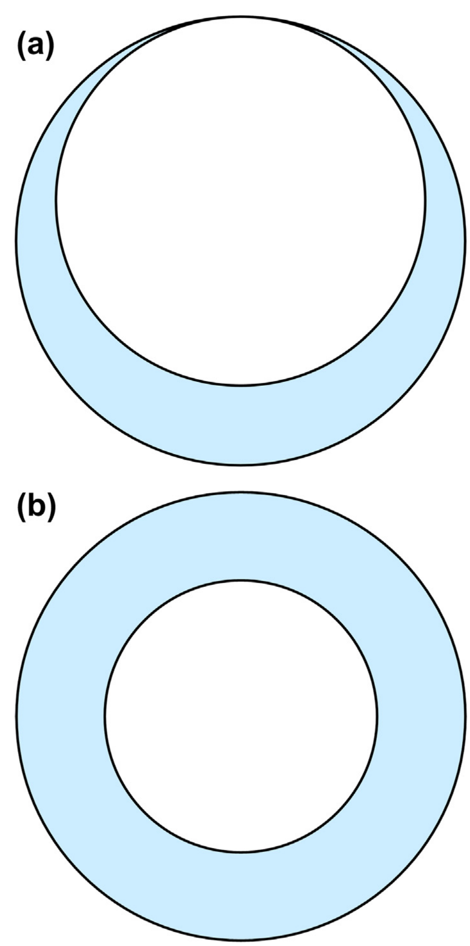

Fig. 1. Flow structures for slug flow and annular flow assumed by De Kerpel et al. [8], the vapour phase is shown in white and the liquid phase in light blue (a) slug flow (b) annular flow. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)